Crab Flares and the Nebular Variability

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The Crab Nebula steady state spectrum and that of the flares

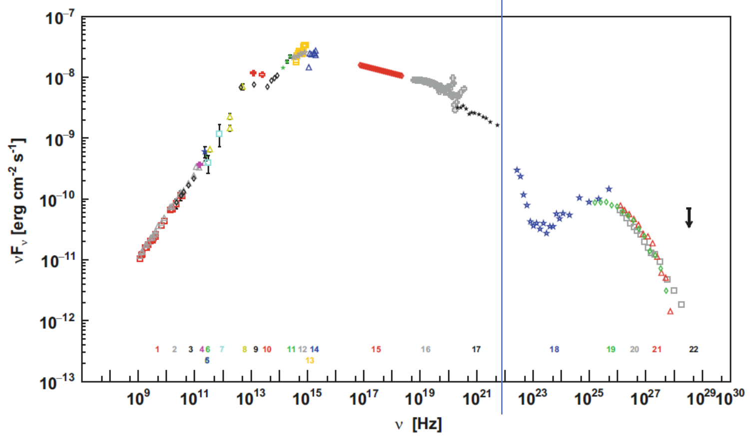


Fig. 6.7 SED of the Crab nebula. Numbers on the bottom indicate the reference where data come from: (1) Baars et al. (1977), (2) Maca-Prez et al. (2010), (3) Wieland et al. (2011), (4) Arendt et al. (2011), (5) Bandiera et al. (2002), (6) Mezger et al. (1986), (7) Wright et al. (1979), (8) Green et al. (2004), (9) Temim et al. (2006), (10) Marsden et al. (1984), (11) Garsdalen (1979), (12) Veron-Cetty and Woltjer (1993), (13) Hennessy et al. (1992), (15) Kirsch et al. (2005), (16) Jourdain and Roques (2009), (17) Kuiper et al. (2001), (18) Buehler et al. (2012), (19) MAGIC Collaboration (2015), (20) HEGRA Collaboration (2004), (21) H.E.S.S. Collaboration (2006), (22) Borione et al. (1997)

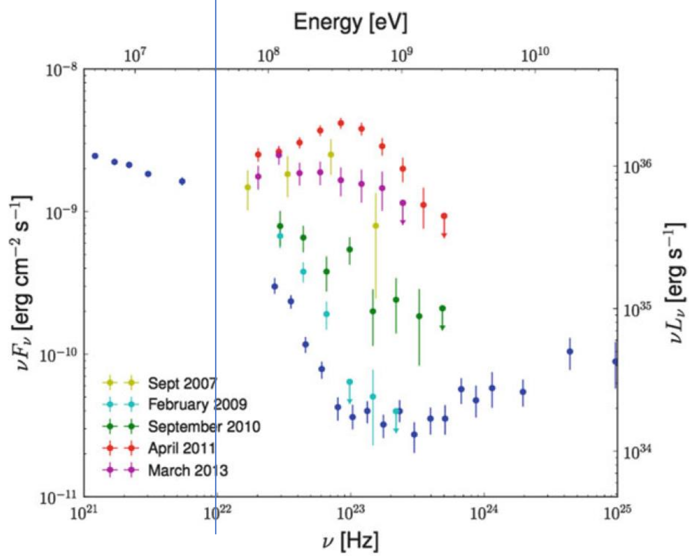


Fig. 6.9 SED at the maximum flux level for five Crab flares. Taken from Bülher and Blandford (2014)

The Flare rise and decay time scales are comparable

$$\tau \sim \frac{10^{15}}{\gamma\, \mathrm{B}_{-3}^{2}} \sim \frac{10^{6}}{\gamma_9\, \mathrm{B}_{-3}^{2}}\ \mathrm{sec}$$

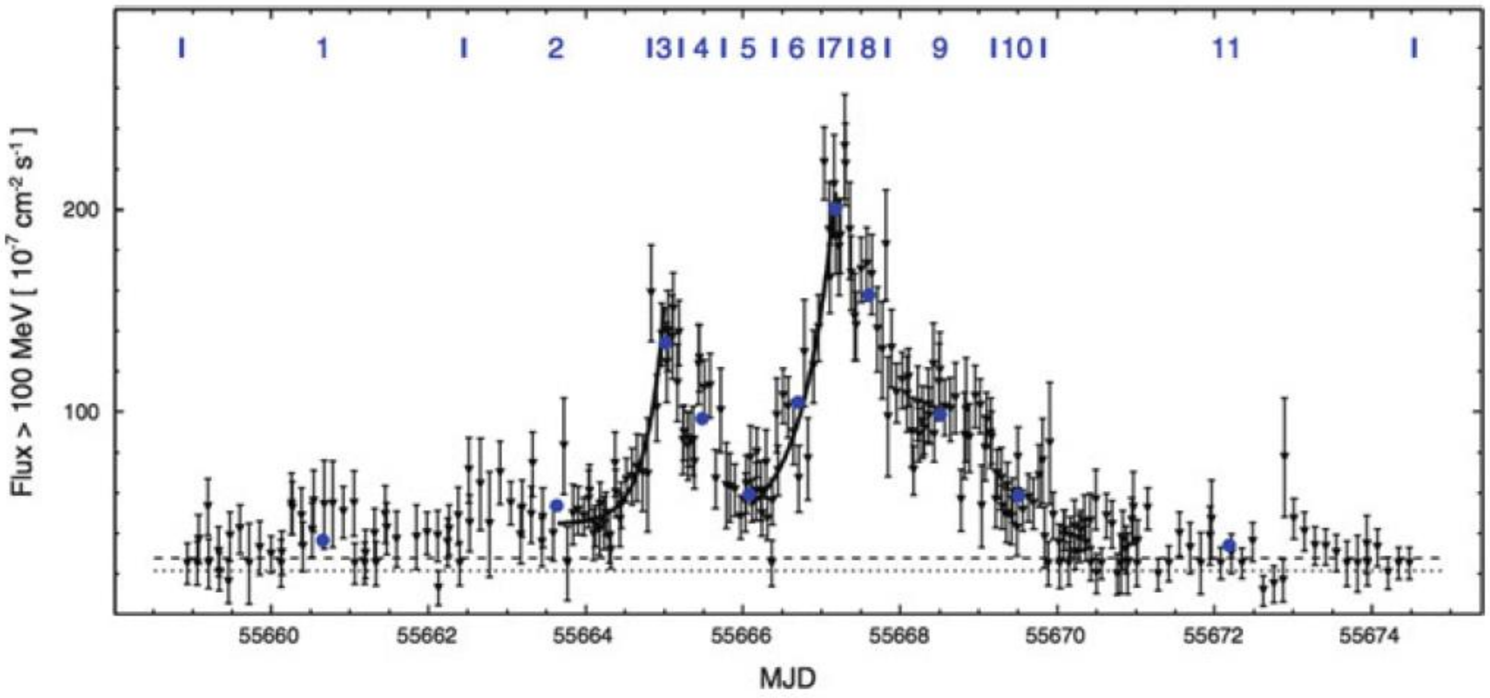
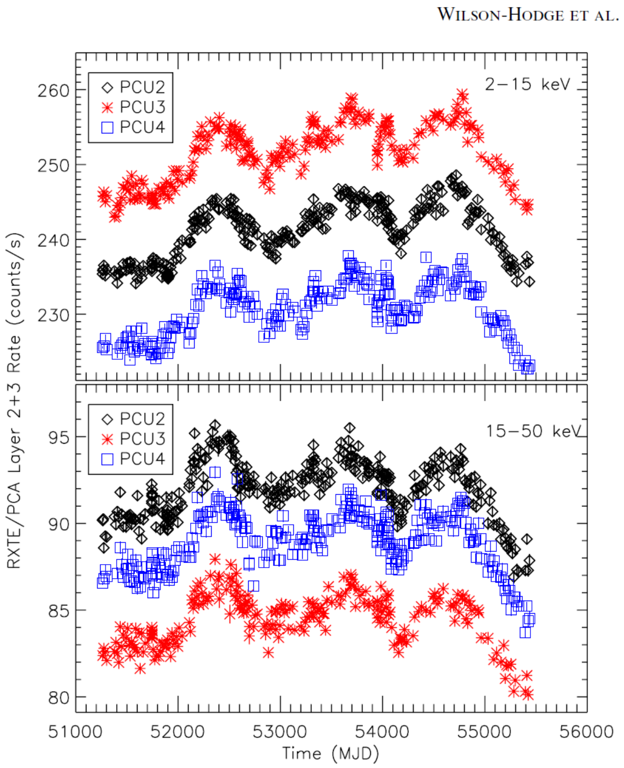


Fig. 6.8 Integral flux of the Crab nebula above 100 MeV as a function of the time during the 2011 April flare. The binning of the plot is 9 min. Taken from Buehler et al. (2012)

Some facts related to the flares

- If the B-field drops linearly from the pulsar LC (*~10^8 cm*) to the MHD shock (*~10^{17} cm*), the field at the shock should be $B \sim 10^{-3}\, B_{-3}$.
- The spectra of the flares are an extrapolation of the nebular spectrum, likely due to the same process, i.e. synchrotron.
- The observed energies are larger than the (B-independent) maximum synchrotron photon energy of particles accelerated in a shock, i.e. $E > m_e c^2/\alpha \sim 70$ *MeV.*
- The flare particles are not accelerated by shock acceleration!
- There have been suggestions of linear increase of the MHD wind Γ with distance (IC + DK 2003) to $\Gamma \sim 10^9$, close to that needed to explain the flares (with $B \sim 10^{-3} B_{-3}$ G, $\nu_s \sim 4\ 10^3\ B_{-3}\,\gamma^2 \sim 10^{22}$ Hz $\rightarrow \gamma \sim 0.5 \times 10^9$).
- If the pulsar wind field lines are good conductors, the polar cap potential ($V \sim 10^{16}$ *Volt*, $\gamma \sim 10^{10}$) is available for discharge should the appropriate field lines get sufficiently close.

The nebula is variable! Amplitude larger at larger photon energies
(Wilson-Hodge et al. 2011)



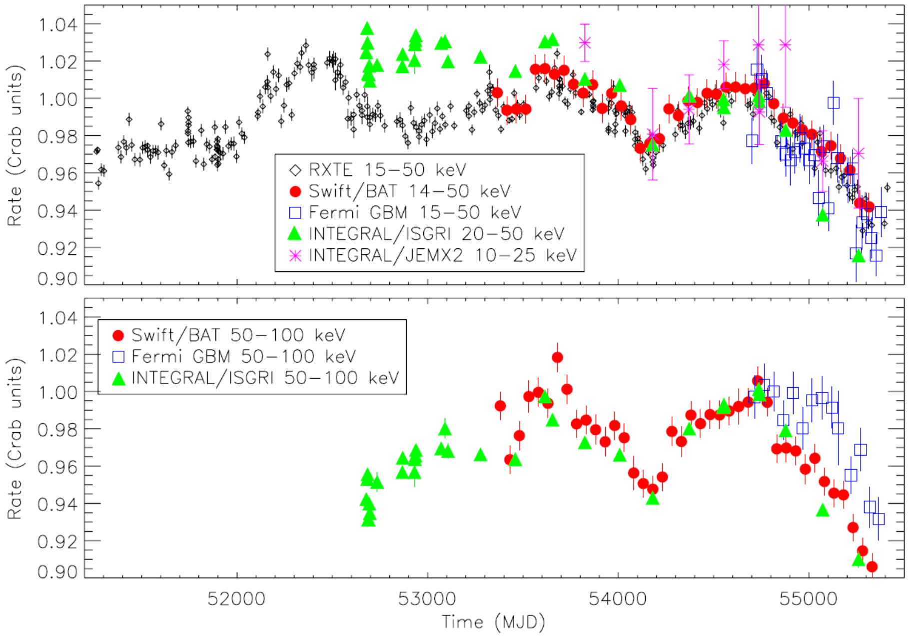
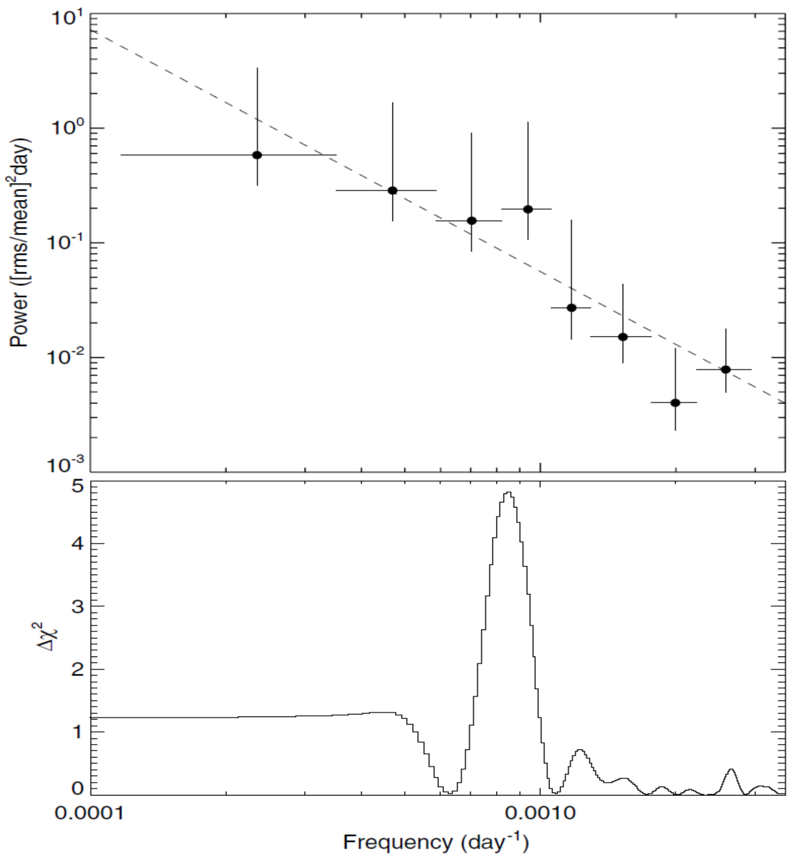


Figure 5. Composite Crab light curves for *RXTE*/PCA (15–50 keV: black diamonds), *Swift*/BAT (top: 14–50 keV, bottom: 50–100 keV: red filled circles), *Fermi*/GBM (top: 15–50 keV, bottom: 50–100 keV: open blue squares), *INTEGRAL*/ISGRI (top: 20–50 keV, Bottom: 50–100 keV: green triangles), and *INTEGRAL*/JEM-X2 (10–25 keV). Each data set has been normalized to its mean rate in the time interval MJD 54690–54790. All error bars include only statistical errors.

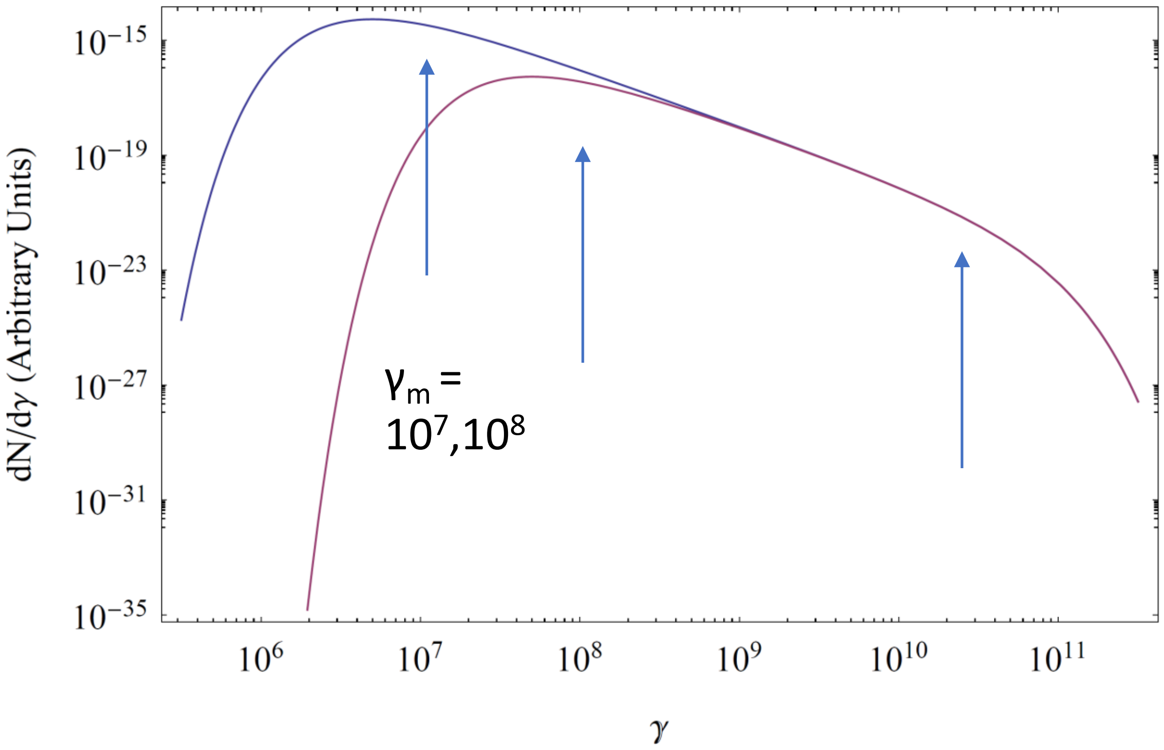
The power spectrum indicates a characteristic time of ~ 1001 nights



The power spectrum of the *RXTE* 15–50 keV rates. The error bars give 68% confidence intervals. The dashed line is the best-fit power law. The bottom panel shows the test statistic for a search for periodic signals.

Is there a relation between the GeV flares and the nebular variability?

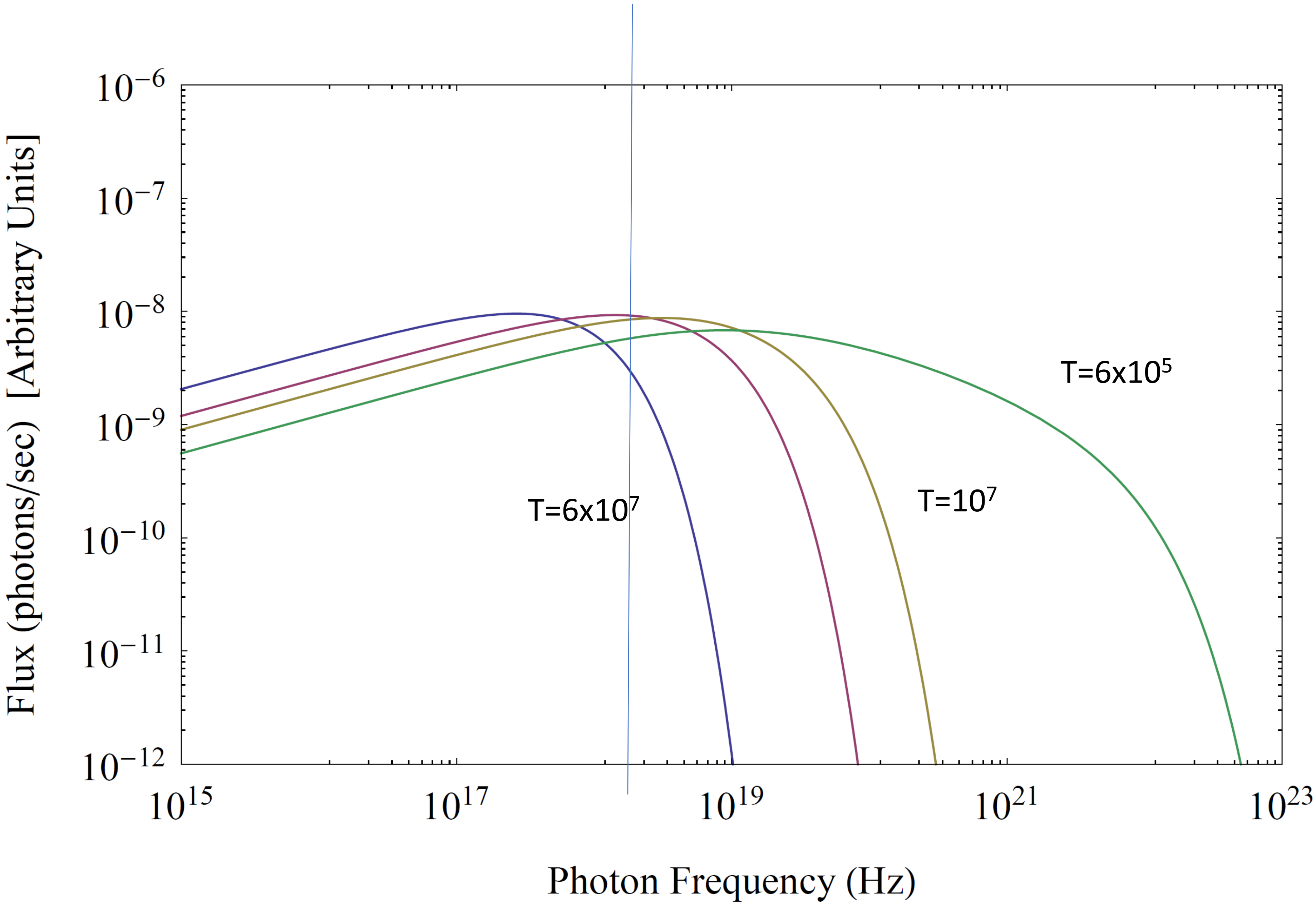
- Assume discharge of the available pulsar voltage at the highest possible energies to provide the flares (*assuming no injection of particles at lower energies)*. The resulting electron distribution will be of the form



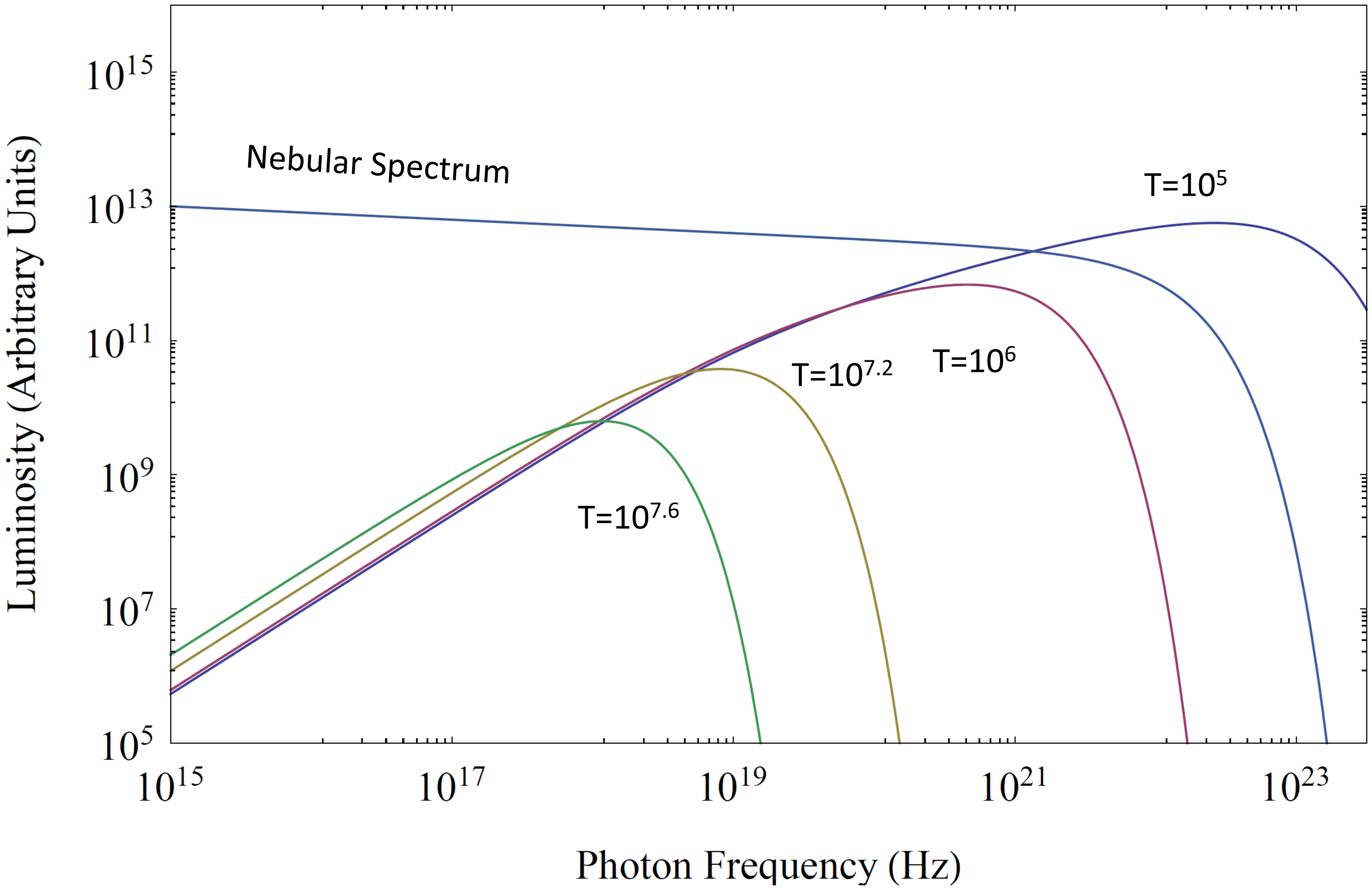
$$F(\gamma) = \gamma^{-2} \times Exp\left[-\left(\frac{\gamma_m}{\gamma} + \frac{\gamma}{\gamma_M}\right)\right]$$

Continue injection for some time and then allow the distribution to evolve under radiative losses

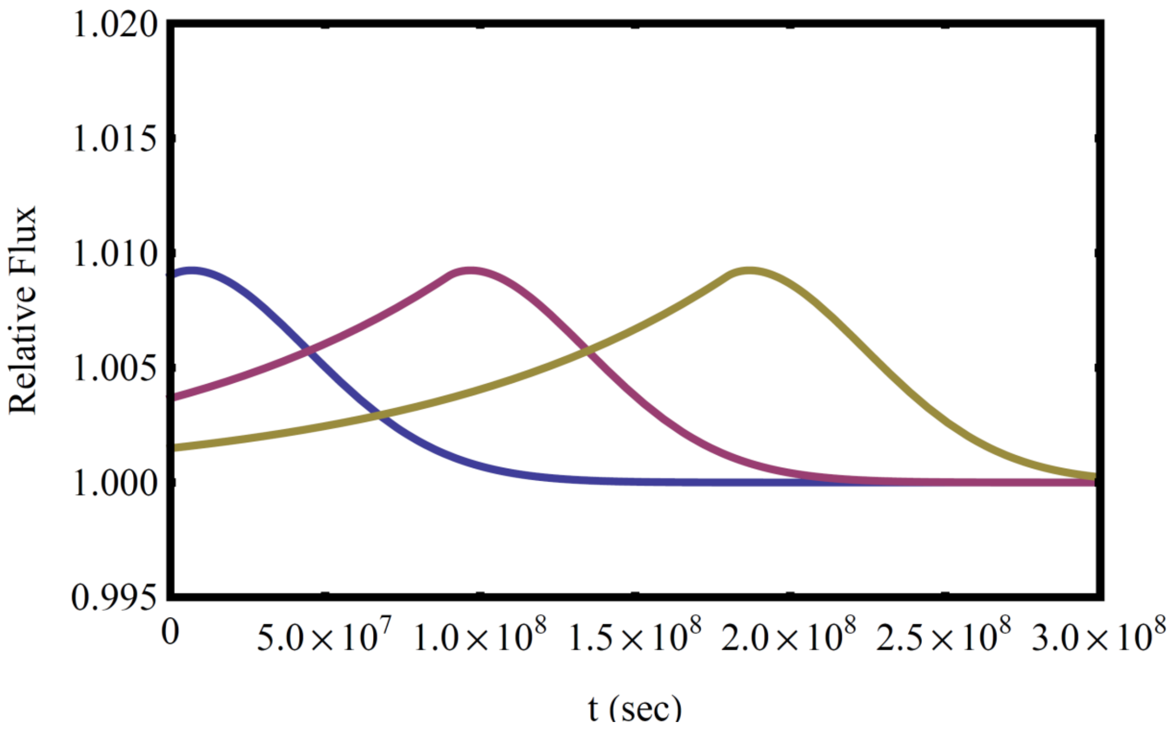
- The electrons obey the following equation
- $\frac{d\gamma}{dt} = -\beta\gamma^2 \Rightarrow \gamma = \frac{\gamma_0}{(1+\beta\gamma_0 t)}$, $\gamma_0 = \frac{\gamma}{(1-\beta\gamma t)}$
- The evolving in time distribution function then has the form
- $DF(\gamma, t) = F\left[\frac{\gamma}{(1-\beta\gamma t)}\right]\frac{1}{(1-\beta\gamma t)^2}$
- Fold the DF with the synchrotron emissivity to produce the synchrotron spectrum of the cooling electrons.

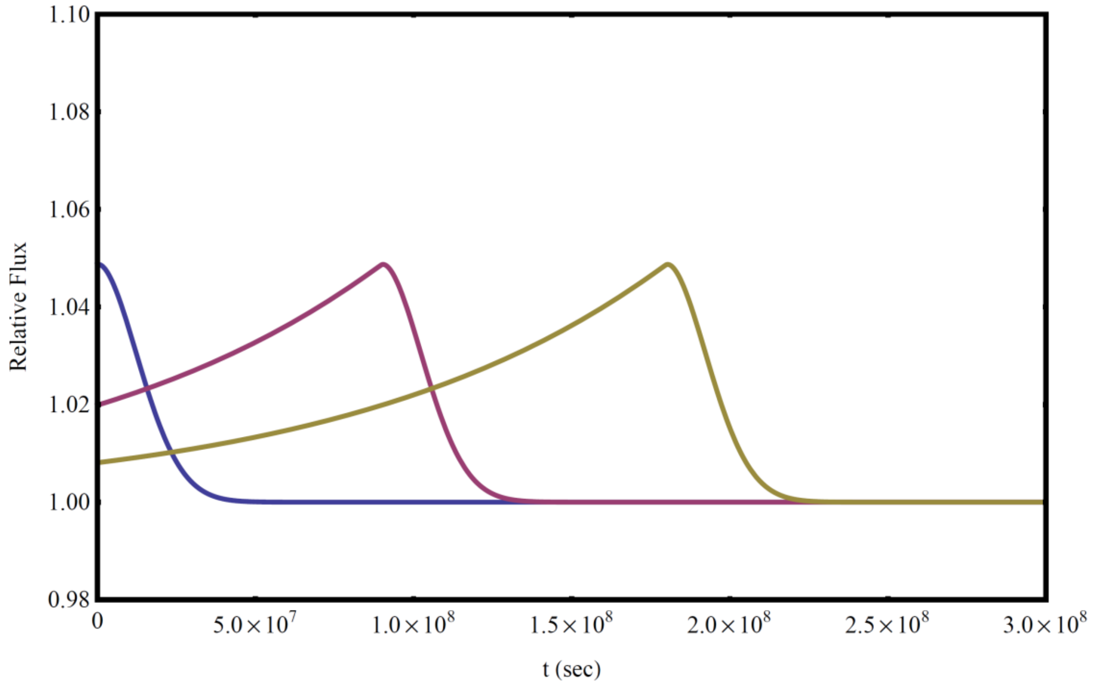


Flux (photons/sec) [Arbitrary Units]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{15}
10^{17}
10^{19}
10^{21}
10^{23}
Photon Frequency (Hz)
T=6x10^5
T=6x10^7
T=10^7


Nebular Spectrum
T=10^5
T=10^6
T=10^7.2
T=10^7.6
Luminosity (Arbitrary Units)
Photon Frequency (Hz)
10^15
10^13
10^11
10^9
10^7
10^5
10^15
10^17
10^19
10^21
10^23

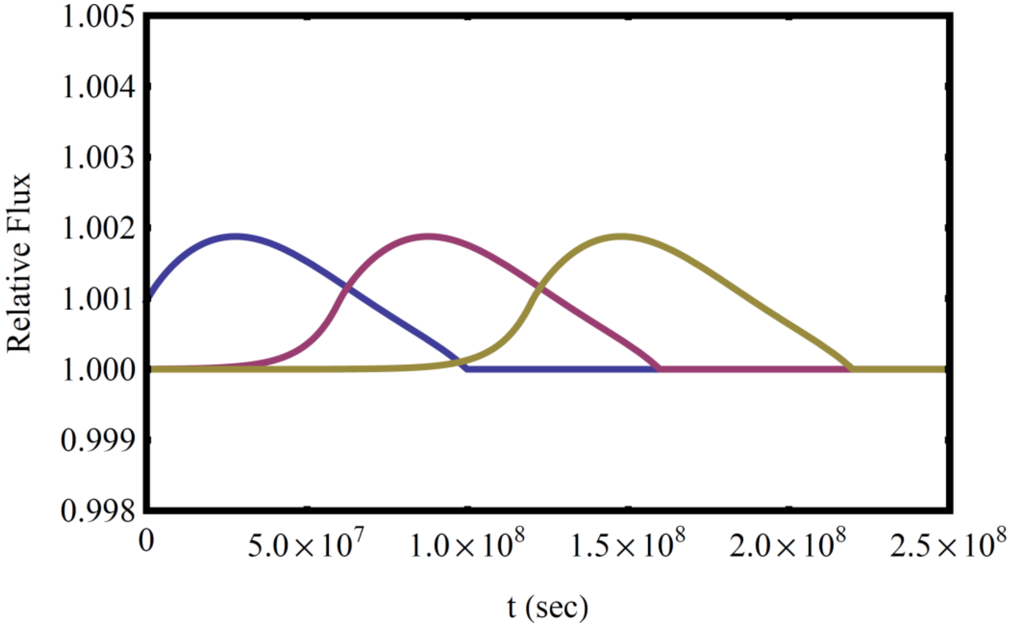
$\gamma_m = 10^7$, $\nu = 10^{18}$ Hz , $\nu = 10^{19}$ Hz



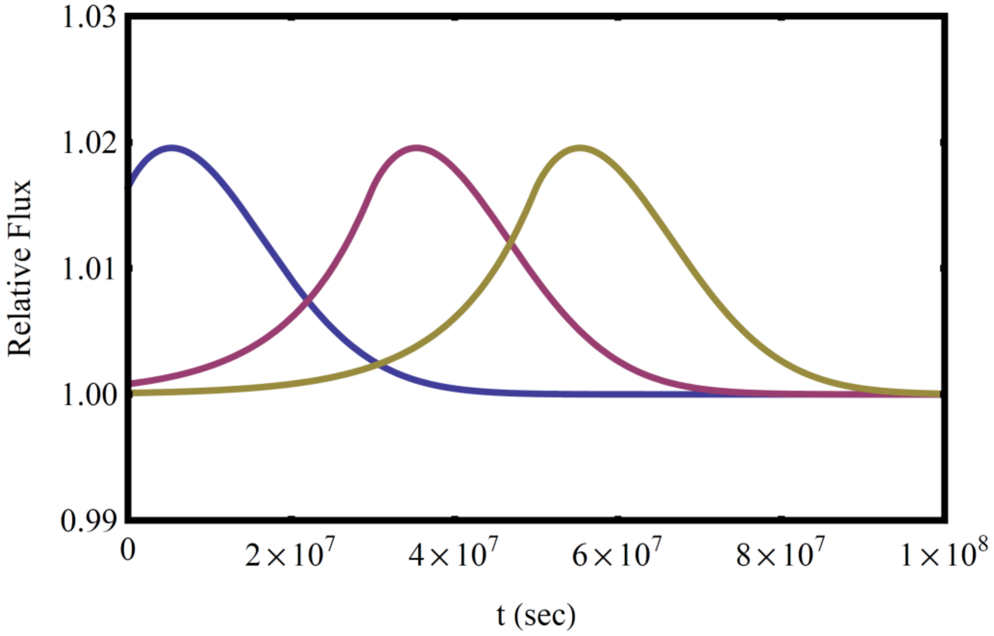


10^5, $9\ 10^7$, $1.8\ 10^8$

$\gamma_m = 10^8$, $\nu = 10^{18}$ Hz , $\nu = 10^{19}$ Hz



10^5, 6 10^7, 2.5 10^8



10^5, 3 10^7, 5 10^7

Conclusions

- There are indications that the Crab flares give rise to the Crab Nebula fluctuations (of relative amplitude ~<4%) observed by a number of spacecraft.
- The long variation periods (~ 1001 days), seen at Swift – BAT, INTEGRAL, Fermi-GBM, along with their observed relative amplitude of the oscillations can constraint significantly the properties of the injected particles, assuming injection at the Crab flares and subsequent cooling.
- There are caveats in the oscillation interpretation which have not been considered so far (*e.g. cooling in a B-field much weaker than that of particle injection; injection with a sufficiently flat particle spectrum i.e. ~* γ^{-2}), which may help the reconcile observed X-ray oscillation amplitudes and time scales with those of flare occurrences.
- Thank you!